Blast-Retrofit of CMU Walls Using Steel Sheets

Authors:

Hani A. Salim, Associate Professor, Department of Civil and Environmental Engineering, University of Missouri-Columbia, Columbia, MO 65211. SalimH@missouri.edu
Robert J. Dinan, Senior Research Engineer, Air Force Research Laboratory, 139 Barnes Drive, Suite 2, Tyndall AFB, FL 32403. Phone: 850-283-3605
John Kennedy, Structural Engineer, Structural Affiliates International, Inc., 2424 Hillsboro Rd. Suite 202, Nashville, TN 37027. jkennedy@saii.com

ABSTRACT

Blast resistant design has come to the forefront of engineering concerns in the wake of recent terrorist threats to the United States. Safety and security are of utmost concern when designing structures, and there has been a significant rise in the demand of researching new methods of reinforcing and retrofitting structures to provide better resistance to blast loading. The focus of this research paper is on the use of steel sheathing as a method of such retrofit. Research is done to ascertain the steel strength, analyze the response of the steel to static pressure, explore strength and ductility limits, investigate connection details, and develop an analytical model of the static resistance function, which will be verified by experimental data. The analytical model for the resistance function will be used in a single-degree of freedom (SDOF) dynamic model to predict the response of steel sheathing blast-retrofitted wall systems.

Coupon tests were performed to establish the stress-strain behavior of the steel material, and component beam tests were used to determine the response of the sheathing under static pressure. In addition, connection methods were analyzed and tested in an effort to determine the most suitable blast-retrofit design for a given blast, without exceeding strength or ductility limits for the steel sheets, and to develop the limit states for the retrofit system. The results of the experimental program and the analytical static and dynamic models were incorporated into a user-friendly wall analysis code for the design of steel sheathing for blast retrofit of CMU walls.

INTRODUCTION

Massive infill walls, such as CMU walls, have low resistance to blast loading and fail catastrophically under blast pressure. A wall's ability to resist the energy imparted by a blast is vital to its structural robustness. These massive infill walls have very little energy absorption capabilities and may produce hazardous projectiles during an explosion, thus causing destruction and injury to the people or property the walls were designed to protect. Therefore, a blast-retrofit system is needed to increase the strength and ductility of the walls, and prevent debris from entering a room. Spray-on and trowel-on polymers have proven to be successful in providing the necessary ductility and energy absorption capability (Davidson et al., 2004). In this paper, however, steel sheathing will be

evaluated as a means of facilitating the need for increasing the ductility and energy absorption of infill masonry wall systems.

This research will determine various properties of steel sheathing, i.e. strength, ductility, response to different connection methods, and pressure-deflection relationships, as they pertain to the blast-retrofit design of a wall system.

APPROACH

To accomplish the aforesaid objectives, an analytical model describing the response of the wall system to static pressure was developed. The analytical model assumes that the static resistance of the wall system is provided by the steel sheet, whereas the CMU wall provides the inertial resistance. Thus, the analytical model is developed to predict the pressure-deflection function for the steel sheathing alone.

For the experimental section, various tests will be conducted for steel component beams, coupons, and connection details. Testing parameters will include three gages of steel sheathing, bolted connection types, and varying the connection parameters, i.e. bolt spacing and thickness of the connection plate. The response of the component beams to pressure will be recorded and used to build the experimental static-resistance function. This will be compared to the analytical model to verify the analytical predictions.

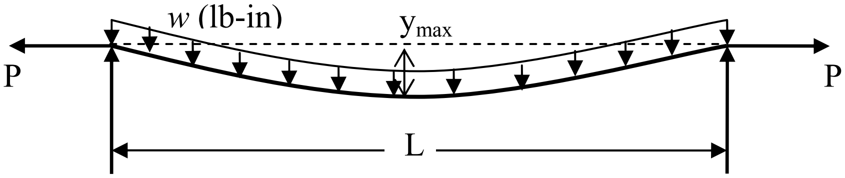
ANALYTICAL MODELING

At the onset of this project, the primary task was to develop an analytical model of the pressure vs. displacement curve, or the static resistance function. Since little was known about the material behavior of the steel sheathing under uniform pressure, two methods of analytical modeling were explored. The first was an approximate model based on the assumption that the material behavior would be first linear elastic and then perfectly plastic. This method utilized a linear elastic equation from Roark's Handbook (Young and Budynas, 2002) as well as a typical equation for a perfectly plastic steel member (Lane 2003). The second analytical method was a detailed analytical model in which an exact equation relating pressure to deflection was derived. Both methods are described below.

Approximate Analytical Modeling

This method focused on known relations of pressure and deflection. Due to the nature of the steel sheathing behavior, two equations would be necessary for the linear elastic part and the plastic part of the pressure-deflection curve. For the elastic region, the steel sheathing was assumed to behave like a cable until yield. Thus, Roark's pressure-deflection relation (case 6) for a cable was used. That relation is given below:

$$p = \frac{64EA}{3L^4} y_{\max}^3 \qquad (1)$$



$$y_{max} = L\left(\frac{3wL}{64EA}\right)^{\frac{1}{3}} \qquad p = L\left(\frac{wL^2}{8y_{max}}\right)^{\frac{1}{3}}$$

FIGURE 1
ILLUSTRATION OF ROARK'S PRESSURE-DEFLECTION RELATIONSHIP FOR A CABLE

When the pressure-deflection curve for this relation is plotted, a cubic function is displayed, which will ultimately represent the elastic section of the final resistance function. The plastic region of the resistance function is based on the assumption that the steel exhibits a perfectly plastic response after yielding. The relationship is given below:

$$y = \left(\frac{wL^2}{8AF_y}\right) \tag{2}$$

where F_y is the yielding stress of the steel. This equation results in a linear pressure-deflection curve and will be ultimately used to represent to plastic section of the final resistance function.

By combining Equations 1 and 2, a pressure-deflection graph is composed. This approximate static resistance function will later be superimposed on the experimental pressure-deflection plot and the detailed modeling curve.

Detailed Analytical Modeling Method

The detailed analytical model follows three principle steps for the derivation of the relation between pressure and deflection. Before the derivation commences, it is necessary to start with an assumed deformed shape for the steel component beam. After the deformed shaped has been established, the first step of the derivation is to explore equilibrium expressions to investigate load-stress relationships. Secondly, a constitutive relation between stress and strain is used to arrive at a relationship between pressure and stress. Next, a compatibility relationship between defection and strain is analyzed, ultimately resulting in the desired relationship between pressure and deflection. This process is outlined through the flowchart in Figure 2.

Based on the assumption that the deflection curve is parabolic in nature:

$$y(x) = \Delta\left(1 - 4\left(\frac{x}{L}\right)^2\right) \tag{3}$$

In this analytical derivation, the strain was assumed to be uniform along the length and thus the stress and the resultant internal tension membrane force T are also assumed uniform. In reality the internal resultant tensile force T varies along the length of the steel sheathing and depends on its location along the length:

$$T(x) = \frac{p\xi L}{\sin(8\delta\xi)}$$

where $\theta(x) = y'(x)$; $\delta = \Delta/L$; and $\xi = x/L$. For small values of Δ the variation of T is very small, whereas for larger values of Δ the value of T can increase by approximately 10%. Therefore, the variation of T along the span will be assumed constant and will take the value at the ends of the beam (x/L = 0.5).

Next, equilibrium equations are applied to the free body diagram of Figure 2.

$$\begin{gathered} \Sigma F_y = 0 \\ 2\,T \sin(\theta) = wL \end{gathered} \tag{4}$$

For small angles, $\sin(\theta)$ can be approximated as simply θ, which is also equal to y'. Furthermore, T can also be rewritten as σA. This means that Eq. 4 can be rewritten as

$$\left(\frac{8\sigma A}{L^2}\right)\Delta = w$$

Note that for a unit width, $b=1$, the area, A, would be equal to $bt = t$, and the distributed load w would be simply $w = pb = p$, where p is the pressure. From substituting these conditions into the above equation, the following expression is achieved:

$$p = \frac{8\sigma \quad t}{L^2}\Delta \tag{5}$$

Next, a relationship between Δ and σ is investigated through the constitutive relation of the material (stress-strain diagram). Consider the stress-strain curve for a typical steel material shown in Figure 3. It is necessary to use compatibility to find a relation between the strain and deflection.

Once the exact strain is determined from this relationship, the corresponding stress can be found from a stress-strain diagram, and Equation 5 is used to determine the pressure at that deflection. Thus, a relationship between pressure and deflection is established. This process is outline next.

Consider the deflected steel sheet in Figure 2. Assuming that the strain is uniform along the length of the beam, it is known from the definition of strain that

$$L' = (1+\varepsilon)(L) \tag{6}$$

Additionally, it is also known from arc properties that the arc length can be given by

$$ArcLength = \int_0^L \sqrt{1+(f'(x)^2)}$$

Solving the integral using the integration limits, and back-substituting it can be shown that

$$L' = 2\left(\frac{-8\Delta}{L^2}\right)\left[\frac{\frac{L}{2}\sqrt{\frac{L^2}{4}+\frac{L^4}{64\Delta^2}}}{2} + \frac{L^4}{128\Delta^2}\ln\left(\frac{L}{2}+\sqrt{\frac{L^2}{4}+\frac{L^4}{64\Delta^2}}\right) - \left(\frac{L^2}{16\Delta}+\frac{L^4}{128\Delta^2}\ln\left(\frac{L^2}{16\Delta}\right)\right)\right]\cdot \tag{7}$$

The following summarizes the steps to determining the detailed analytical model for calculating the load-deflection response of the steel sheet:

1. Set Δ equal to zero, and incrementally increase its value by a small amount
2. Use Equation 7 to determine the corresponding value for L'
3. Use Equation 6 to calculate the strain

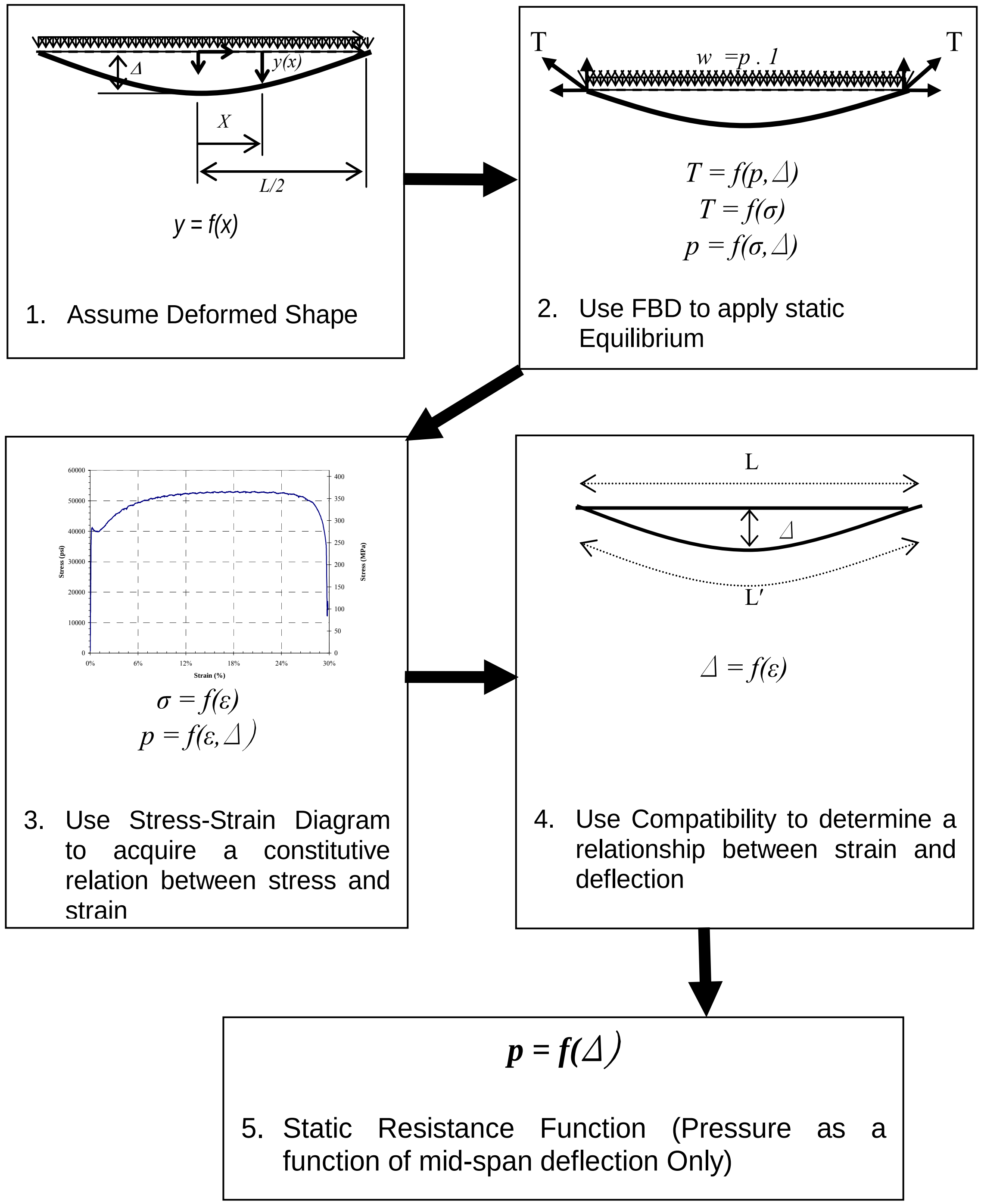


FIGURE 2

FLOWCHART FOR THE DERIVATION OF PRESSURE-DEFLECTION RELATIONSHIP

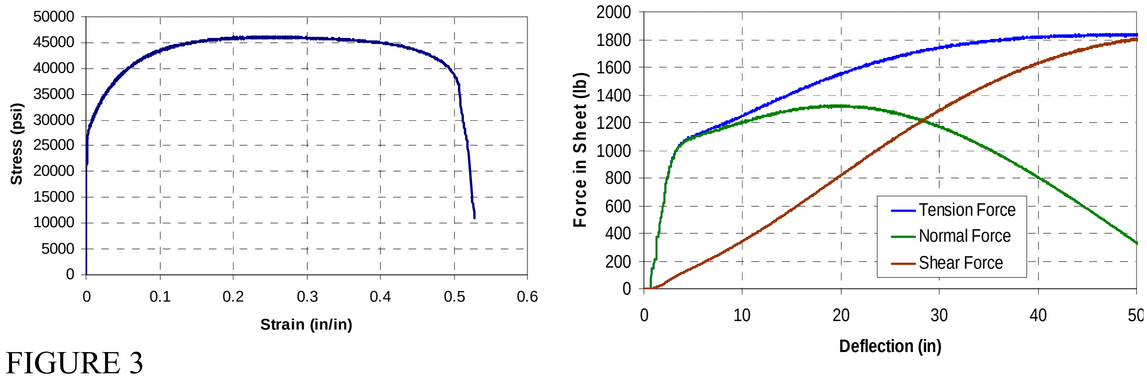


FIGURE 3

TYPICAL ENGINEERING STRESS-STRAIN RELATION FOR A 20-GAGE STEEL SHEET (LEFT); ANALYTICAL TENSION MEMBRANE FORCE IN STEEL SHEET (RIGHT)

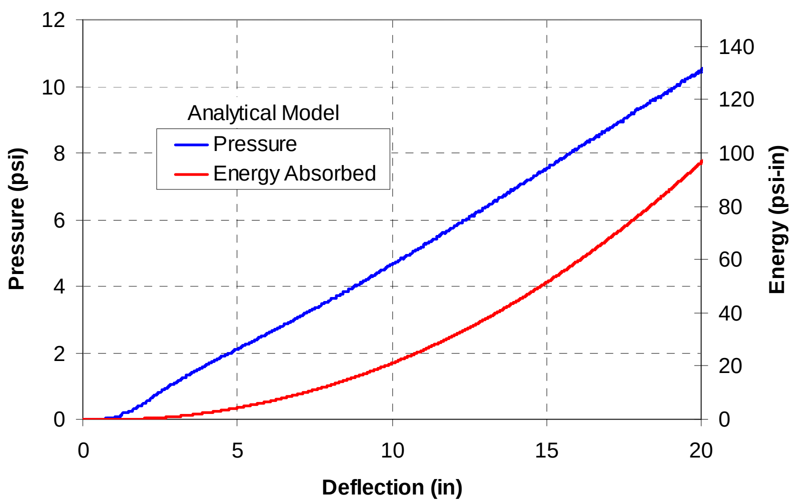


FIGURE 4

ANALYTICAL STATIC RESISTANCE FUNCTION FOR STEEL SHEET OF FIGURE 3

4. From the stress-strain curve (similar to Figure 3), find the stress corresponding to the calculated strain
5. Use Equation 5 to calculate the pressure
6. Increment Δ and start at step 1 again. Repeat the process until the ductility limit is reached, which represents failure of the steel sheet.
7. Plot the calculated pressures versus the incremented deflections to failure

Using the procedure described above, an analytical static resistance function is produced. The variation of the tension membrane force and its components in the steel sheet are shown in Figure 3. A sample of this plot is shown in Figure 4. This resistance function was verified experimentally using coupon-, connection-, and component-level tests.

EXPERIMENTAL EVALUATION

Coupons were cut from the same parent material as the component beam and connection specimens used in this study following ASTM standards. The stress-strain relation of the

steel sheets was measured to develop the analytical static resistance function in conjunction with connection and component testing.

For the connection testing, steel sheathing samples were connected to the loading frame using clamping steel plates and ¾ inch bolts tightened to a constant torque of 1600 lb-in. The samples were pulled in tension until failure. The setup and sample mode of failure are shown in Figure 5. The steel sheathing was tested in 3 different gage thicknesses: 18, 20, and 22. With regard to connection details, the following parameters were tested: 12 and 16 inches bolt spacing; ¼ and ⅛ inch thickness of the clamping plate. The sharp edges of the clamping plates were beveled using a grinder, alleviating the sharp force applied to the steel sheathing which caused brittle failure in some cases. A sample response curve of a connection test is shown in Figure 5, and the results of the tests performed are shown in Table 1.

For the component beam testing, a setup was designed using a 16-point loading tree that imposes a simulated uniform load across the length of the beam. A 10 feet long steel sheathing sample was connected to the ends and loaded in bending until failure (Figure 6). The load and the deflection at three locations were recorded and the a typical results is shown in Figure 7 along with the analytical prediction using the detailed and approximate methods.

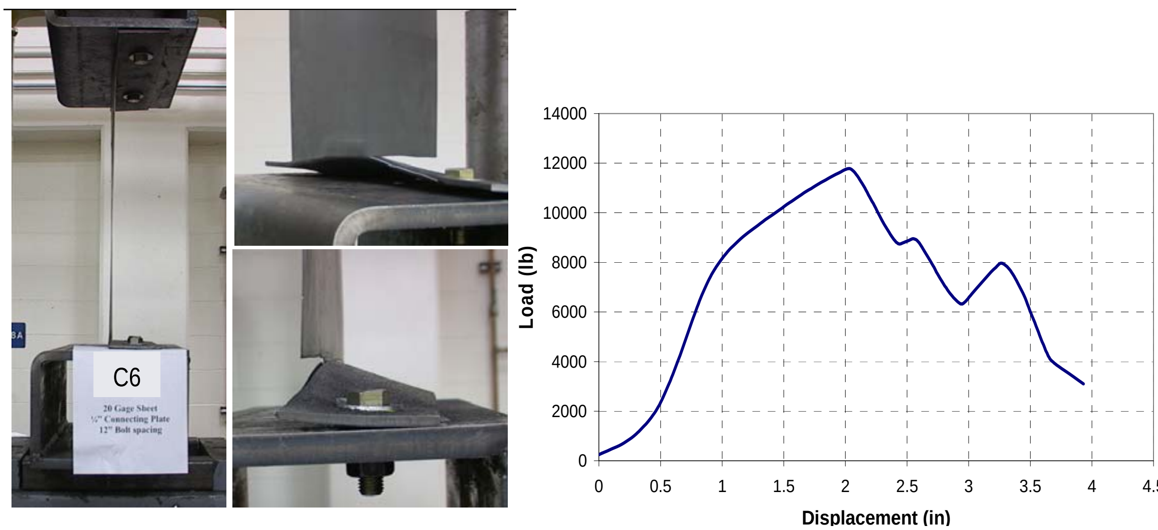


FIGURE 5
CONNECTION TEST SETUP SHOWING TEARING AT BENT (LEFT); RESPONSE OF CONNECTION 6 (RIGHT)

Connection Sample	Sample Width	Anchor Plate (in)	Gage (Thick, in)	Bolt Spacing (in)	Max Load (lbs)	Max Deflection (in)		Failure Type
						Initial	Total	
Connection 4	16”	½-thick	22 (0.03)	12	13,100	2.0	0.2	Brittle
Connection 6	20”	¼-thick	22 (0.03)	16	11,900	2.2	3.8	Soft Tearing
Connection 7	16		20 (0.035)	12	12,200	3.1	5.2	Brittle
Connection 8	20”			16	10,600	2.6	5.1	Soft Tearing
Connection 9	16”		18 (0.045)	12	12,900	2.4	4.9	Brittle
Connection 10	20”			16	10,900	2.5	4.3	Soft Tearing
Connection 11	20”	1/8-thick	22 (0.03)	16	4,900	1.5	2.7	Bearing
Connection 12	16”			12	10,100	2.2	4.8	Soft Tearing
Connection 13	20”		20 (0.035)	16	9,200	4.2	5	Brittle
Connection 14	16”			12	13,800	4.2	5.1	Brittle

TABLE 1
RESULTS OF CONNECTION TESTING

FIGURE 6
ILLUSTRATION OF THE COMPONENT BEAM TREE TEST SETUP

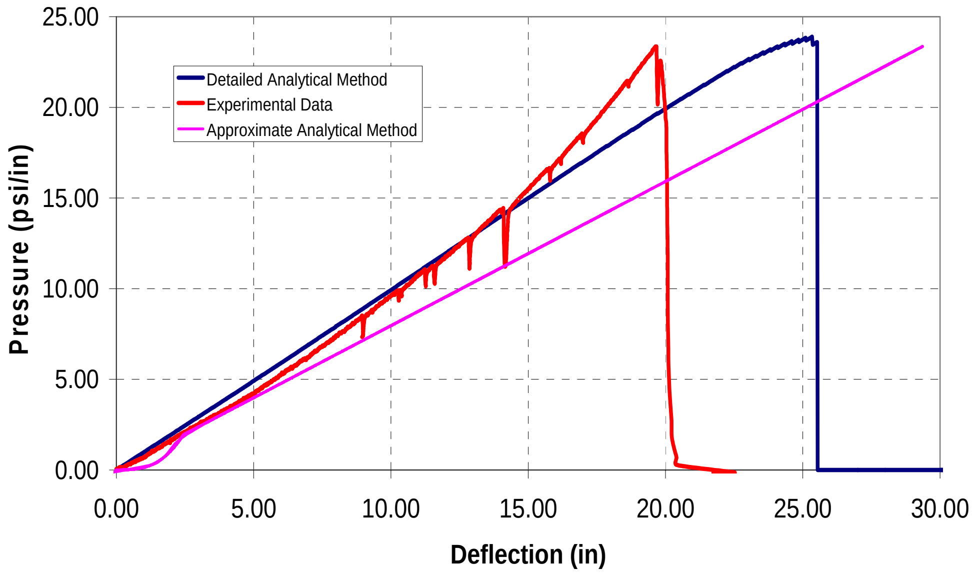


FIGURE 7
COMPARISON OF BOTH ANALYTICAL MODELS WITH EXPERIMENTAL DATA OF THE RESISTANCE FUNCTION

BLAST-RETROFITTED WALL EXAMPLE

To illustrate the research effort outlined in this paper, an example of a 12-foot high unreinforced CMU wall retrofitted with 20-gage steel sheets anchored top and bottom using 6 in × ¼ in steel plates and 5/8 inch bolts spaced at 12 inches on centers. The CMU wall is assumed to respond in one-way bending and to provide only inertial resistance to the blast. The energy-absorption capability of the wall system is mainly contributed by the tension membrane resistance of the un-bonded steel sheet retrofit. Figure 3 shows the variation of the tension membrane force and its components as a function of the wall midpoint deflection. The material response of the steel sheets is shown in Figure 3, and the analytical model of the static resistance function is shown in Figure 4 along with the energy absorbed by the steel sheets during the response to blast.

The response of the wall under a planned future test is predicted in this paper. The analytical model for the static resistance function was used in a SDOF dynamic model to predict the dynamic response of the blast-retrofitted wall under the specified threat level. The analytical model predicts a maximum deflection of 12.14 inches (Figure 8) and a maximum support rotation of 9.5 degrees. According to the component beam tree tests, the steel sheet and connection combination can deflect up to a maximum deflection of 20 inches. Therefore, it is expected that this CMU wall-steel sheet retrofit system will survive the specified explosion threat.

DISCUSSION

The analytical model developed in this paper matches closely the experimental resistance function. The resistance function traces the behavior of the steel sheet during the elastic, plastic, strain hardening, and softening regions of the response to failure. The resistance

of the retrofitted wall is provided by the inertia of the CMU blocks and the tension membrane resistance of the steel sheets. The analytical SDOF model does not account for the energy absorbed during the fracture of the outside face of the CMU blocks, and thus the predictions are expected to be conservative. The resistance of the steel sheets is limited by the capacity of the connection, and thus the clamping plate and concrete anchors should be designed to prevent premature failure at the ends. Failure limit states are controlled by the ductility limit of the steel sheets, tensile and shear strength of the sheets, and connection capacity. Proper combination of anchorage and plate dimensions is necessary to utilize as much as practically possible the capacity of the steel sheets and to increase the ductility and energy-absorption capabilities of the wall.

The analytical resistance function is combined with a SDOF model to predict the response under blast load. The mid span deflection prediction for a full-scale wall retrofitted with steel sheets under a blast indicate that it will survive the blast threat. Field tests to verify the analytical predictions are necessary to validate the response under blast loads. Additional research is needed to account for all possible energy absorption capabilities of the wall, such as during debonding of the mortar joints and fracture of the blast-side face of the CMU blocks.

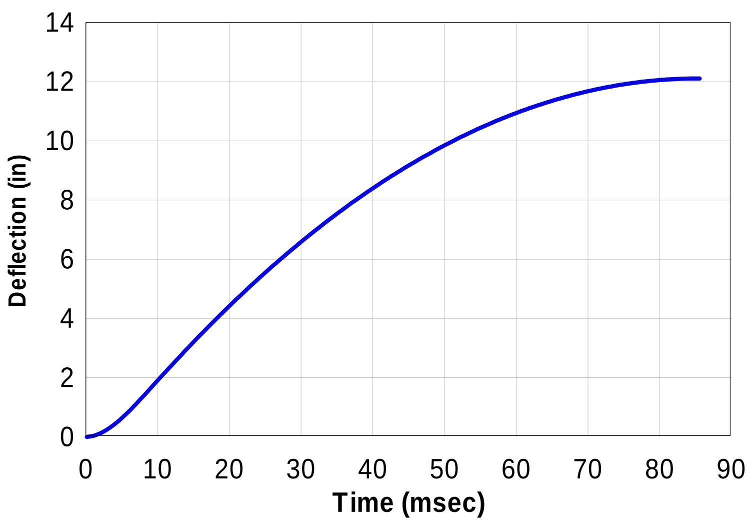


FIGURE 8
DYNAMIC RESPONSE OF CMU-STEEL SHEET WALL SYSTEM UNDER BLAST LOADING

REFERENCES

[1] Biggs, J.M. (1964). “Introduction to Structural Dynamics.” McGraw-Hill College.

[2] Davidson, J.S., Porter, J.R., Dinan, R.J., Hammons, M.I., and Connell, J.D. (2004). “Explosive Testing of Polymer Retrofit Masonry Walls.” ASCE Journal of Performance of Constructed Facilities, Vol. 18, No. 2.

[3] Lane, J (2003). *Modeling and Design of Explosion Resistant Steel Stud Wall Systems.* University of Missouri, Columbia, MO.

[4] Young, W.C. and Budynas, R.G. (2002). *Roark’s Formulas for Stress and Strain.* 7th Ed., McGraw-Hill, NY.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
17-02-2006	PREPRINT Technical Paper	1 Jan 2005 - 17 Feb 2006

4. TITLE AND SUBTITLE
Blast-Retrofit of CMU Walls Using Steel Sheets

5a. CONTRACT NUMBER
F08637-03-C-6006

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
63112F

6. AUTHOR(S)
Salim, Hani A., Dinan, Robert J., Kennedy, John.

5d. PROJECT NUMBER
4918

5e. TASK NUMBER
C1

5f. WORK UNIT NUMBER
4918C10B

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Department of Civil and Environmental Engineering
University of Missouri-Columbia
E2509 Engineering Building East
Columbia, MO 65211-2200

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Materials and Manufacturing Directorate
139 Barnes Drive, Suite 2
Tyndall AFB, FL 32403-5323

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-ML-TY-TP-2006-4518

12. DISTRIBUTION/AVAILABILITY STATEMENT
Distribution Statement A: Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES
PREPRINT. Technical paper to be published in conference proceedings of the 2006 Structures Congress, American Society of Civil Engineers, St Louis MO, 18-20 May 2006.

14. ABSTRACT
This research paper discusses the use of steel sheathing as retrofit/reinforcing method to increase structural blast resistance. Research has been conducted to ascertain the steel strength, analyze the response of the steel to static pressure, explore strength and ductility limits, investigate connection details, and develop an analytical model of the static resistance function, which will be verified by experimental data. The analytical model for the resistance function will be used in a single-degree of freedom (SDOF) dynamic model to predict the response of steel sheathing blast-retrofitted wall systems. The results of the experimental program and the analytical static and dynamic models were incorporated into a user-friendly wall analysis code for the design of steel sheathing for blast retrofit of CMU walls.

15. SUBJECT TERMS
Sheet Steel Retofit; Blast Resistant Design; Blast Retrofit Wall System; Single-degree of Freedom Dynamic Model

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	SAR	11	Elizabeth Trawinski
					19b. TELEPHONE NUMBER *(Include area code)* 850-283-3611